PROGRESS IN LIDAR ALTIMETER REMOTE SENSING OF STAND STRUCTURE IN DECIDUOUS AND CONIFEROUS FORESTS USING SLICER DATA.

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ABSTRACT

Large footprint, waveform sampling lidar altimetry has a number of benefits over traditional, small footprint, single return laser altimetry for the remote sensing of forest structure. Nevertheless, its application has been impeded by a lack of 1) algorithms for converting the lidar data to biophysical measurements, 2) validation of the resulting measurements, and 3) applications demonstrating the utility of the measurements. Over the course of the last five years, we have developed algorithms and software packages for the extraction of height, cover, canopy height profile and light transmittance related measurements, and validated them using field measurements in two contrasting forested ecosystems: eastern deciduous forests in Maryland and North Carolina, USA; and western coniferous Douglas-fir/western hemlock forests at H.J. Andrews Experimental Forest, Oregon, USA. In both systems, field measurements of forest height and cover were accurately estimated by the lidar measurements. In eastern deciduous forest, SLICER was able to accurately predict canopy height profiles, ie. the vertical distribution of foliage. In addition, estimates of the vertical distribution of PAR transmittance derived from the lidar measurements matched field measurements, in terms of the height and rate of change in transmittance, in both systems. Interpretative methods to describe canopy structure have ranged from simple estimates of the total height and mean height of the canopy, to a complex method describing the entire three-dimensional distribution of canopy elements (canopy volume method). These basic measurements of the physical structure of the canopy have been used to predict a wide range of forest stand structure attributes, including basal area, aboveground biomass, leaf area index, mean and standard deviation of tree diameters at breast height, and density of large individuals. The ability of lidar to predict these variable has been very good, as compared with non-lidar remotely sensed estimates, with coefficients of determination usually in excess of 80% of variance explained. Through this work, the utility of waveform sampling lidar altimetry has been established, and the impediments to its use have been substantially decreased.

1. INTRODUCTION

Characterization of canopy structure is a major challenge in remote sensing, particularly for moderate to high biomass forests. A new class of instruments, referred to here as lidar altimeters, developed at NASA's Goddard Flight Space Center (Bufton, 1989; Blair et al., 1994; 1997) have demonstrated a potential to greatly improve remotely sensed estimates of important aspects of canopy structure. These devices measure the vertical distribution of canopy structure directly using the principles of laser altimetry. The capability of traditional laser altimeters, that measure a single range to a target, is expanded by recording the laser backscatter amplitude with very high temporal resolution. The approach yields a measure of the height distribution of illuminated surfaces within the laser footprint. Recent work has demonstrated that this measure can be used to accurately predict both the total biomass (Lefsky, 1997; Lefsky et al., 1999a; Means et al., 1999; Lefsky 1999b) and variability of forest structure (Lefsky, 1999b) over a large range of biomass. In this paper, the measurement principles of lidar altimeters as applied to canopies and a review of several

validations of their ability to measure various aspects of canopy structure and forest stand structure are presented.

This description and validation of the SLICER (Scanning Lidar Imager of Canopies by Echo Recovery) canopy measurements provides a summary for the use of SLICER data in studies of forest canopy structure, including the work of Harding et al. (1994; 1995), Lefsky (1997), Lefsky et al., (1999a; 1999b), Harding (1998), Drake and Weishampel (1998), Means et al., (1999), and Rodriguez et al., (in review) and for future studies. The principles developed here also apply to canopy lidar data being acquired by the airborne Lidar Vegetation Imaging System (LVIS) and to be acquired by the spaceborne Vegetation Canopy Lidar (VCL). LVIS is a wide-swath, mapping system developed at GSFC that has superseded SLICER (Blair et al., 1999). VCL, scheduled for launch in 2000, is expected to inventory canopy height and structure over approximately 5% of the Earth's land surface between ±68° during its 2 year mission (Dubayah et al., 1997).

2. SLICER BACKGROUND

The SLICER airborne lidar altimeter system consists of a ranging component and ancillary instrumentation for geolocation. The ranging component consists of a laser transmitter, scan mechanism, receiver telescope, detector, timing electronics, waveform digitizer, and an instrument control and data collection system. The ranging instrumentation is augmented by an Inertial Navigation System for precise determination of laser beam pointing, GPS receivers for differential, kinematic determination of aircraft position, and video equipment for image documentation of the ground track. Integration of the ranging data with laser beam pointing and aircraft position yields a position and elevation for each laser pulse return with respect to a geodetic reference frame. Key aspects of the SLICER system are reviewed below; complete documentation of the instrumentation and data products is provided in Harding et al., (In Review). SLICER data sets available for public distribution are described at http://denali.gsfc.nasa.gov/lapf.

Several aspects of the SLICER design make it a powerful tool for characterizing canopy vertical structure. The combination of a very narrow transmit pulse and a high-speed detector results in exceptional vertical resolution, allowing closely spaced canopy layers and the underlying ground within each footprint to be distinguished. Use of a very high-speed digitizer results in a non-aliased waveform record of backscatter energy that has extremely good vertical sampling, necessary for full analysis of waveform structure. SLICER evolved from a profiling lidar altimeter described by Blair et al., (1994) by the addition of a scanning mechanism. By scanning the laser footprints across the flight path a narrow swath results which provides both cross- and along-track information on canopy heterogeneity and ground slope beneath the canopy. SLICER employs a high power laser that enables a significantly higher flight altitude than is typical used by airborne laser altimeters, yielding larger footprints (nominally 10 m but as large as 70 m) that are contiguous or even overlapped. The larger footprints thus fully illuminate the canopy, providing a measure of average canopy structure that avoids the sampling bias inherent to small footprint altimeters. The canopy in these large footprints typically contains some openings at nadir to the ground thus consistently yielding a ground return and enabling a measure of vegetation height for each laser pulse. In addition, the high flight altitude minimizes the variation in footprint size and received backscatter energy caused by changes in ranging distance due to topographic relief, thus simplifying data interpretation. Accurate pointing and position knowledge, and associated geolocation software, enable accurate determination of the location of each footprint so that the lidar data can be directly correlated with ground observations and remote sensing images. SLICER's control systems and operational modes were designed to be flexible so that the effect of variations in footprint size, spacing and vertical sampling on characterization of canopy structure could be evaluated.

Several implications of the instrument characteristics are significant for proper use of the SLICER data. First, the laser illumination across the swath is not uniform and thus canopy structure across the swath is sampled unequally. The pattern of circular, approximately contiguous footprints that each have a radial, Gaussian distribution of laser energy yields a swath illumination that is analogous to an inverted egg carton. Second, the backscatter amplitude recorded in the waveform is not an absolute measure of reflected laser energy. The transfer function between optical energy received by the instrument (i.e. backscattered photons) and the resulting digital count amplitude in the waveform is unknown due to uncalibrated instrument parameters. The transfer function varies spatially, as a function of beam position across the swath, and temporally on multiple time-scales, as a function of operating conditions. Thus, the amplitudes of waveforms can not be compared in an absolute sense. The waveform can only be used as a relative measure of the height distribution of backscattered energy within an individual footprint.

Third, SLICER utilizes a threshold detection scheme to define the range to the first detected target within a footprint. Therefore, the detection of the canopy top requires that sufficient backscatter energy be received exceeding the detection threshold. The backscatter intensity depends on intercepted area and the near infrared (NIR) reflectance of the intercepted surfaces at 0° phase angle. Thus SLICER's ability to detect the canopy top, and the resulting derivation of canopy height, depends on the geometry of the outer canopy surface and the reflectivity of the components making up the outer surface. For example, narrow, erect conifer tips with NIR-dark needles are less easily detected than a concentration of NIR-bright deciduous leaves forming a well defined, umbrella-like crown top. Depending on these canopy characteristics, the SLICER measurement of canopy height can be biased low to varying degrees as compared to the outer-most canopy surface.

3. WAVEFORM LIDAR PROCESSING ALGORITHMS

Waveform Height Algorithm

To process the waveform into an estimate of the total height of the vegetation sampled, a sequence of processing steps is applied to the raw waveform data (Lefsky, 1997, Harding et al., Submitted). First, to improve the signal-to-noise ratio of the distribution, the raw amplitudes (Fig. 1a) are summed by accumulating the signal in adjacent waveform bins. Generally, either 6 or 9 adjacent bins have been summed, yielding either a 66 or 99 cm vertical sampling. The 66cm vertical sampling is approximately equal to the vertical resolution defined by the laser pulse width and detector response, while the 99 cm sampling has been used for compatibility with non-lidar field measurements. Next, the mean and variance of the background noise is established using the final portion of the waveform, beyond any potential last ground return. The mean background noise is subtracted from the summed distribution yielding signal above the noise level (Fig. 1b).

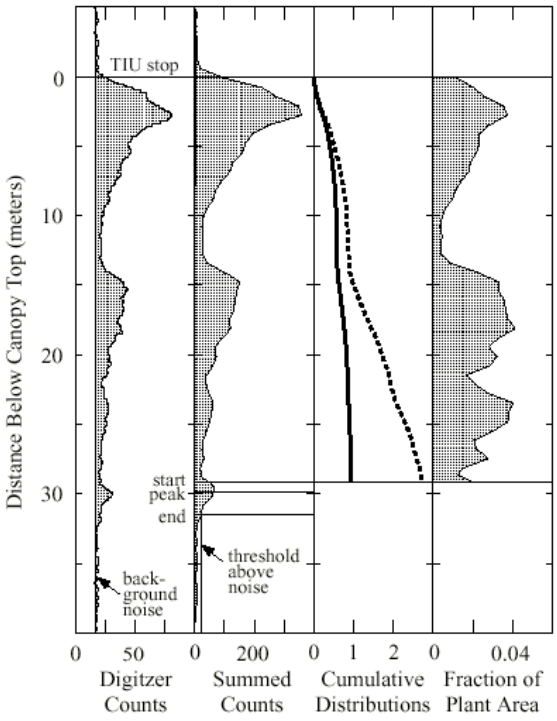

Fig. 1. Steps in converting a raw SLICER waveform to various processing levels (Panels a-d left to right) Harding et al., (In Prep.)

We then distinguish the ground reflection in the signal by assuming that it is the last return above noise. The end of the last return is defined as the last signal above a threshold that is a multiple of the background noise variance (Fig. 1b). The peak of the last return is defined to be the first inflection in signal strength prior to the end of the last return, identified using its first derivative. The start of the last return can not be uniquely identified from the raw distribution because backscatter return from low vegetation could be convolved in time with the ground return. Therefore, the start of the last return is identified based on the width characteristics of the system impulse response. The impulse response is the theoretical signal recorded from a smooth and flat surface and depends on the convolved effects of pulse width and detector response. The SLICER impulse response is established from water surface returns. A ratio is determined for the impulse response between the width from the signal end to peak as compared to the width from peak to start. The observed end-to-peak width of the last return is scaled by this ratio in order to define the start position of the last return. This method accounts for any pulse broadening of the last return due to slope or roughness of the ground within the footprint. After automated identification of the last returns, the results are interactively evaluated, and modified where necessary, by examining profile plots of last return start, peak, and end elevations. Anomalous variations in elevation or last return width, either along or across the SLICER swath, reveal improperly identified ground returns that are then manually corrected. Recently, morphological filtering operations have been applied to the problem of correcting anomalous ground return estimates, eliminating the need for manual correction

The amplitude of the ground reflection is then scaled to account for the difference between average canopy and ground NIR reflectance at 0° phase angle. In the existing work with SLICER, the ground return amplitude was increased by a factor of two based on the assumption that the reflectance of the ground, dominantly comprised of leaf-litter with some bare soil and rare live foliage, was half that of the canopy. The results of our work have been relatively insensitive to potential errors in this reflectance scaling factor, as described in Harding et al., (Submitted).

Intercepted Surfaces / Transmittance Algorithm

A cumulative height distribution for the canopy return can then be calculated, normalized by the adjusted total return (canopy + scaled ground), yielding a height distribution of canopy closure (Figure 1c). This Normalized Cumulative Power Distribution (NCPD) can be further transformed to estimate the vertical distribution of transmittance at the sensor orientation. The NCPD is used to estimate transmittance as follows:

$$T_{SLICER}(h)=1\text{-}NCDP_{h+1}$$

where $T_{SLICER}(h)$ is the SLICER estimate of transmittance at height h and NCPD(h+1) is the normalized cumulative power distribution at h+1. Since SLICER measures the reflectance of the laser at each height (assuming the contribution of multiple scattering to signal delay is small), T_{SLICER} at a height is equal to one minus the cumulative reflectance from the height above it. In reality, transmittance is equal to one minus the sum of cumulative reflectance and absorbence. The NCPD can be used as a proxy for the sum of cumulative reflectance and absorbence when the ratio of absorbence to reflectance does not vary with height. Where the assumption of a constant ratio is violated, the error in T_{SLICER} compared to actual transmittance should be small because absorbence by foliage and needles at

the 1064 nm laser wavelength is very low, typically in the range 0.01 to 0.1 (e.g., Williams, 1991)

Canopy Height Profile Algorithm

In order to derive canopy height profiles from the raw SLICER waveform distributions we adapted the MacArthur and Horn (1969) transformation method. Two assumptions inherent to the transformation (Aber, 1979) also apply to the transformation of SLICER waveforms. The horizontal distribution of canopy components within a layer is assumed to be random with respect to layers above and below. In other words a Poisson distribution is assumed with no horizontal clumping of canopy components. Also, the leaf inclination distribution is assumed to be constant as a function of height so that the projected leaf area in the direction of observation (up-looking from the ground or down-looking for SLICER) is related in a constant way to total leaf area. Several additional assumptions specific to the SLICER waveforms must also be made. As a replacement for the proportion of clear-sky to plant interception sightings, defining gap fraction viewed upward from the ground, the proportion of ground return to canopy return signal strength is used. However, in order for this proportion to represent downward-viewed gap fraction the ground return signal strength is modified in order to account for any difference in the average reflectance at 0° phase angle (i.e., direct backscatter) of the ground and canopy at the laser wavelength. In most circumstances this ratio between ground and canopy reflectance is not known at the scale of the laser footprints and a value must be assumed. Application of the method to SLICER waveforms also assumes that the reflectance of the canopy components is constant as a function of height. Whereas for the ground sightings each canopy intercept counts equally in the resulting distribution, for SLICER an equivalent surface area contributes greater return signal as reflectance increases. This assumption inherently implies that the ratio of woody to leafy surface area and the woody and leafy reflectances are constant as a function of height. Finally, it is assumed that multiple scattering, causing lengthened photon travel paths, does not contribute significantly to delayed signal in the waveform, because either the amount of multiply-scattered photons received in the backscatter direction is small as compared to singly-scattered photons or the magnitude of any resulting delay is small. Implications for each of these assumptions are considered in Harding et al., (Submitted).

The effect of occlusion (the decrease in return energy that occurs with increasing depth in the canopy, and which is due to the previous interception of the laser energy) on the NCPD is corrected by weighting this distribution by -1 x ln(1- closure) (MacArthur and Horn, 1969; Aber, 1979), transforming the result to a cumulative distribution of canopy area projected in the direction of the laser beam (Fig. 1c). The cumulative distribution is normalized and converted to an incremental height distribution, yielding the Canopy Height Profile (CHP), which depicts the fraction of projected canopy area per measurement interval (Fig. 1d). The heights of the CHP intervals are referenced to the absolute backscatter energy and no comparison of energy between laser shots is made.

Software Implementations of Waveform Processing Algorithms

There are two main software implementations of these processing algorithms. IMH (Interactive MacArthur-Horn), developed by D. Harding and M. Lefsky, computes stand height and canopy height profiles, and has served as the software for most applications of the processing algorithms. The IMH functions are included in the latest version of a SLICER data browser and editor implemented in the Interactive Data Language (IDL) that is available at http://denali.gsfc.nasa.gov/lapf. XLV (X-windows Lidar Viewer) is an extension of those routines developed by M. Lefsky, and includes the ability to predict transmittance profiles and canopy volume measurements (see below).

4. VALIDATION OF WAVEFORM LIDAR MEASUREMENTS

Height

Lefsky (1997) examined field and lidar measurements of maximum stand height for a dataset consisting of twelve field plots with coincident lidar measurements in eastern deciduous forests of Maryland and North Carolina, USA. He found good correlation (r^2= 78%) between field and lidar measurements, but a tendency for the lidar measurements to underestimate the height of the tallest stands. Field measurements of maximum height were derived from estimates of the canopy height profile, using the optical quadrat method (MacArthur and Horn, 1969) and were therefore not as accurate as those obtained using methods based on the trigonometric principle. Means et al., (1999) found high correlation (r^2=95%) and excellent agreement between lidar estimates of height and field estimates of "canopy height" (mean height of dominant and co-dominant trees) obtained using the trigonometric principle. Subsequent analysis of that dataset (Lefsky, Unpublished) indicates high correlation between lidar and field estimates of maximum stand height (r^2=94%), and that the relationships between field and lidar estimated maximum height and canopy height are not significantly different from identity.

Cover

Plant cover has been estimated as the total adjusted power of the ground return, divided by the total power of the canopy return. Lefsky (1997) found good agreement between field and lidar measurements of cover (R^2=65%), and, with the exception of two clearly outlining points, found a relationship near identity for the lidar and field estimates of cover. Means et al., (1999) found excellent agreement between lidar and field estimates of cover (R^2=94), with negligible difference between field and lidar estimates of cover (RMS=0.08).

Transmittance

Parker et al., (In Prep) have examined the relationship between field and lidar measurements of the vertical distribution of transmittance in both eastern deciduous and western coniferous forests. Although the lidar measurements estimate the transmittance of direct illumination at the nadir angle of the sensors, and the field measurements estimate the transmittance of both direct and diffuse illumination at the sun azimuth angle, the two measurements closely track each other, both in terms of the total vertical distribution of transmittance, and several key derived statistics (Fig. 2).

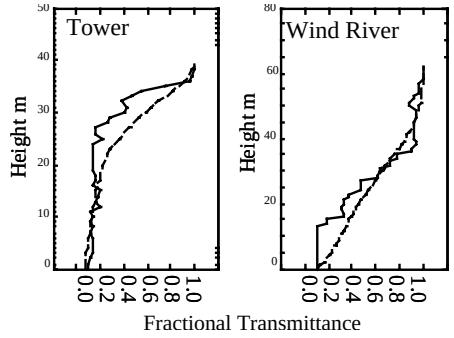

Fig. 2. Comparison of field (solid) and lidar (dashed) estimates of transmittance as a function of height in an eastern (Tower) and western (Wind River) forest. Parker et al (In Prep)

Canopy Height Profiles

Validation of the ability of SLICER to estimate field measurements of the canopy height profile (CHP) are presented in Lefsky (1997) and Harding et al., (Submitted). Despite the inherent difficulties in comparing the upward looking field estimates and the downward looking lidar estimates of the CHP, good agreement between the two estimates was found for four stands of differing age (Fig. 3). They also found that SLICER estimates of the CHP fell within the range of variability observed when different subsets of the field CHP data were compared. Lefsky (1997) applied a smoothing algorithm to both field and lidar estimates of the CHP, and found no statistically significant differences between the field and lidar estimates of the CHP.

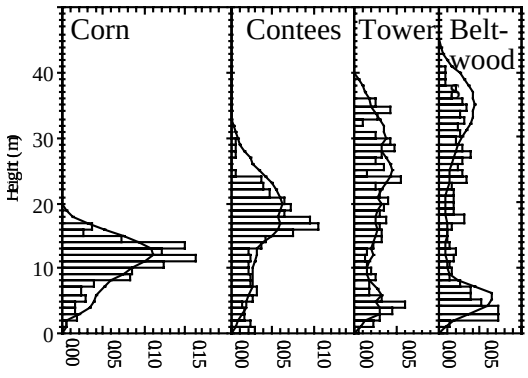

Fig. 3. Comparison of lidar (line) and field (bars) estimates of the canopy height profile. Harding et al. (Submitted)

5. APPLICATIONS OF WAVEFORM LIDAR MEASUREMENTS

Three published studies document the utility of SLICER for prediction of forest stand structure. Lefsky (1997) and Lefsky et al., (1999a) used data from SLICER to predict aboveground biomass and basal area, using indices derived from the canopy height profile, in eastern deciduous forests. In Lefsky et al., (1999a), a number of height related indices were evaluated for the prediction of stand basal area and biomass, and the quadratic mean canopy height was found to be the best overall predictor. The quadratic mean canopy height is the mean height of the canopy height profile, with each element of the profile weighted by its squared height. Of particular note, they found that relationships between height indices and forest structure attributes (basal area and aboveground biomass), could be generated using field estimates of the CHP, and applied directly to the lidar estimates of the CHP, resulting in unbiased estimates of forest structure. Means et al., (1999) applied similar methods to 26 plots in forests of Douglas-fir and western hemlock, at the H.J. Andrews experimental forest. They found that very accurate estimates of basal area, aboveground biomass and foliage biomass could be made using lidar height and cover estimates.

The third published study (Lefsky et al., 1999b) is the first to take advantage of SLICER's ability to measure the three-dimensional distribution of canopy structure in a direct fashion (Figure 4). Five-by-five blocks of waveforms (corresponding to a 50 x 50 m field plot) were processed using the novel canopy volume profile algorithm. Following the procedures above, each waveform was transformed into an estimate of the canopy height profile (CHP), the relative distribution of the canopy as a function of height. A threshold value was then used to classify each element of the CHP into either "filled" or "empty" volume, depending on the presence or absence (in the waveform) of returned energy. A second step classifies the filled elements of the matrix into an "euphotic" zone, which contains all filled elements of the profile that are within the uppermost 65 % of canopy closure, and an "oligophotic" zone, consisting of the balance of the filled elements of the profile. These two classifications were then combined to form three classes; empty volume beneath the canopy- (i.e., closed gap space), filled volume within the euphotic zone, and filled volume within the oligophotic zone.

These same classes are then computed for each of the twenty five SLICER waveforms in the 5 by 5 array. The waveforms were then compared, and a fourth class was added, "open" gap volume is defined as the empty space between the top of each of the waveforms and the maximum height in the array. At this point, the total volume of each of the four classes of canopy structure can be tabulated for each 5 by 5 array of waveforms. To determine the ability of SLICER measured canopy structure indices to predict aboveground biomass and Leaf Area Index (LAI), stepwise multiple regressions were performed using as independent variables the total volume of each of the four

canopy structure classes and the total volume occupied by vegetation material, as measured by the combined volume of the euphotic and oligophotic zones.

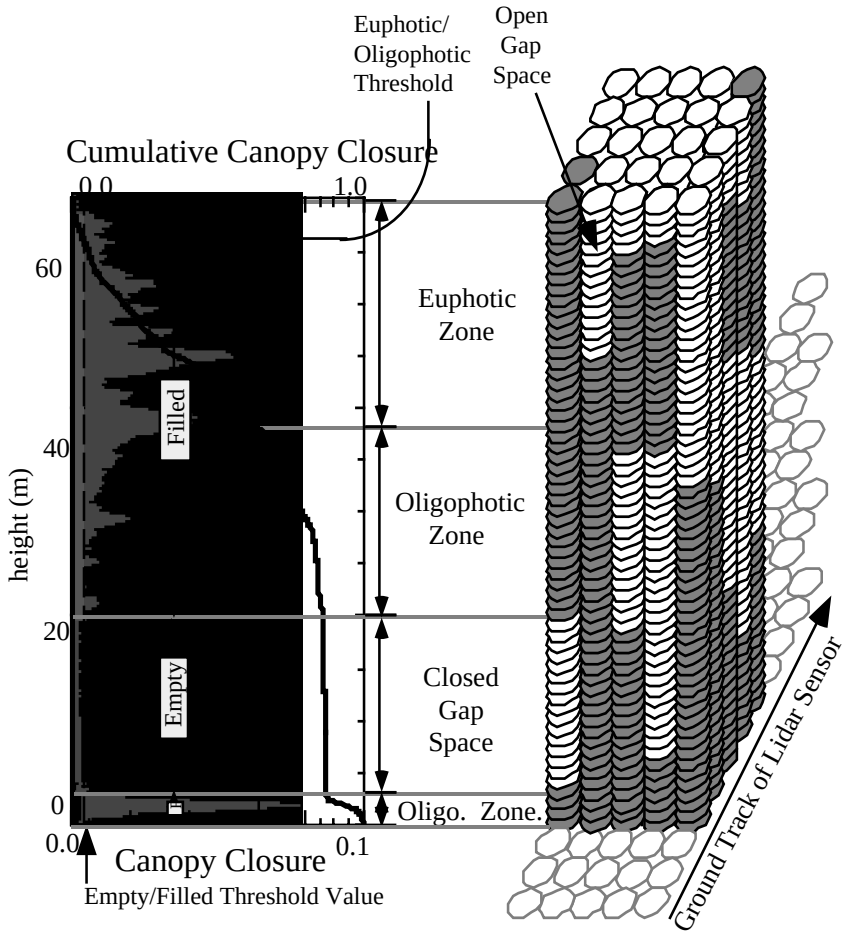

Fig. 4. The Canopy Volume Method (Lefsky et al., 1999b)

Fig. 5 presents canopy volume profile diagrams for representative young, mature and old-growth plots. These diagrams indicate, for each 1 meter vertical interval, the percent of each plot's 25 waveforms that belong to each of the four canopy structure classes. Young stands are characterized by short stature, a uniform canopy surface (as indicated by the height distribution of the interface between the euphotic zone and open gap space), and an absence of empty space within the canopy (ie. closed gap space). Mature stands are taller, but still are characterized by a uniform upper canopy surface. In contrast to young stands, mature stands have a large volume of closed gap space. Mature stands of Douglas-fir often have a high density of large trees with uniform DBH. The uniformity of size leads to the uniform canopy surface height, and the interception of light and other resources by these trees results in the absence of canopy material at lower levels. Old-growth stands are distinguished from mature stands by their uneven canopy surface, and the wide vertical distribution of each of the four canopy structure classes. Whereas stands from earlier stages in stand development have canopy structure classes in distinct vertical layers, in the old-growth stands each canopy structure class occurs throughout the height range of the stands. The continuous distribution of canopy surfaces from the top of the canopy to the ground has been cited as a key physical feature of old-growth forests distinguishing them from the simpler canopies of young and mature stands (Spies and Franklin, 1991)

Scatterplots of predicted vs observed stand structure attributes are presented in Fig. 6. The strength of the relationships developed here are very strong in comparison to other remote sensing techniques, and compare favorably with allometric equations relating complementary aspects of individual tree geometry. Examination of the scatterplots indicates that the predicted values of aboveground biomass and LAI show no asymptotic tendency, even at extremely large values (1200 Mg/ha Biomass, LAI of 12). The equation predicting biomass involved positive correlations with the total filled volume, and the number of waveforms taller than 55 m. The equation predicting LAI involved a positive correlation with the total filled volume and the open gap volume, and a negative correlation with the closed gap volume. This may be interpreted as suggesting that the all-sided surface area of leaves is proportional to the volume they are distributed in. Increases in the vertical range of the upper canopy surface tends to increase

LAI, and the presence of empty spaces within the canopy tends to decrease LAI. Although both LAI and aboveground biomass use the total filled volume variable in their equations, scatterplots and regressions have shown that the predicted values of each variable are no more highly correlated with each other than the original data.

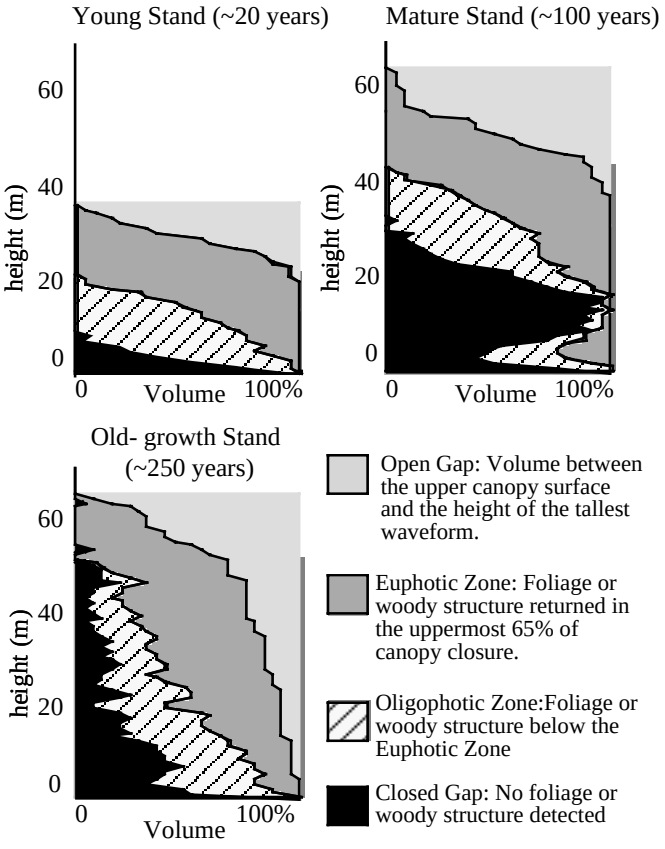

Fig. 5. Canopy Volume Profiles (Lefsky et al., 1999b)

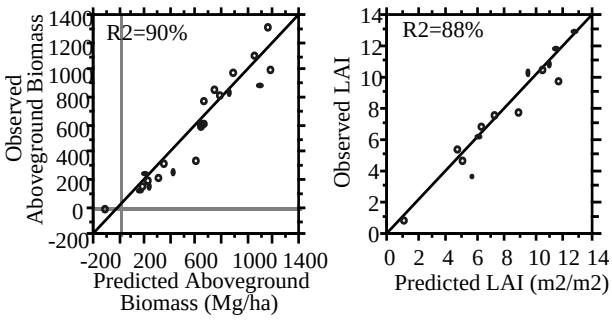

Fig. 6. Predictions of Stand Structure from Canopy Volume Method

6. CONCLUSION

The development of forest ecology applications of lidar remote sensing will depend on detailed knowledge of canopy organization, and the interaction of lidar sensors with that organization. Using data from the SLICER device, we have made several introductory studies of the interaction of the sensor with two very different canopy types, and developed algorithms that relate lidar measurements to standard field measurements of forest canopies. Additionally, we have shown the utility of these measurements for the estimation of forest stand structure attributes, such as aboveground biomass and LAI, in both forest types.

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